

Campbell 2.1.6.
(11-13)

From the Author

June 17. 1876.

J. F. Campbell

[*From the* QUARTERLY JOURNAL *of the* GEOLOGICAL SOCIETY *for*
May 1876.]

ON COLUMNAR, FISSILE, AND
SPHEROIDAL STRUCTURE.

On COLUMNAR, FISSILE, and SPHEROIDAL STRUCTURE. By the Rev. T. G. BONNEY, M.A., F.G.S., Fellow and Tutor of St. John's College, Cambridge.

THE subject of the columnar jointing and spheroidal structure of rocks has of late received considerable attention, the most important papers on the subject being those by Professor James Thomson* and by Mr. R. Mallet†. The former explains the columnar structure by a contraction of the mass in cooling, and advances a novel theory to account for the cup-and-ball structure observed in cross-jointing, viz.—that the fracture commenced at the centre, owing to a longitudinal tensile stress, starting often from a “small [included] mass of stone different in texture and in hardness from the rest” of the rock, and proceeded outwards towards the periphery. The cause of this tensile stress he considers to be, probably, chemical action set up by infiltration of water, which has produced an expansion of the outside of the column, so that the outer part, growing longer, has strained and finally snapped the interior. The spheroidal structure, often manifested in decaying basalts, he considered not to be “an original concretionary structure, but due to decomposition penetrating from without inwards in blocks or fragments, into which the rock has been fissured.”

Mr. R. Mallet commences his paper by an ingenious mathematical demonstration of the cause of hexagonal fracture in the contracting body. He then passes on to consider the cup-and-ball structure. This he regards as a further product of contraction from loss of heat in a prism which is now cooling from the sides as well as from an end, so that the curved surface of the joint is always concave to the end which is losing heat; and he regards the spheroidal structure as the result of the residual forces of contraction which yet remain in the imperfectly cooled prismatic blocks into which the column is divided.

That columnar structure was due to contraction was clearly pointed out many years since by Mr. Scrope in his admirable work on the Auvergne‡; so that the confused statements in subsequent text-books of geology well deserve the severe comments of the above-named authors. With their explanation I fully concur; and the demonstration of Mr. R. Mallet seems to me unanswerable. I shall therefore pass rapidly over this part of the subject, merely calling attention to one or two points of interest in connexion with columnar structure. As, however, I entirely dissent from Professor J. Thomson's conclusions in the rest of his paper, and differ to some extent from those of Mr. Mallet, I venture to think there is yet room for a few remarks on the subject—one which I have for some time past lost no opportunity of studying.

* Report of Belfast Naturalists' Field Club, 1869-70.

† Phil. Mag. ser. 4, vol. 1. pp. 122, 201.

‡ Volcanoes of Central France, p. 92.

I shall begin by describing the various structures which may be observed in rocks, more especially volcanic, and then consider how far they can be explained by the theory of contraction, as stated by the above-named authors. The advantage of this method will be that we shall see more clearly what phenomena have to be explained. I shall consider the spheroidal structure apart from the others.

It is almost needless to remark that though columnar structure* appears to be most frequent in basalt, it is not confined to that rock; I have myself seen it in trachyte (district of Mont Dor, Auvergne), pitchstone (Arran), felstone (Cader Idris, &c.), phonolite (Roche Saudoire &c., Auvergne). Nor is it confined to igneous rock. I have observed it in volcanic mud (beneath a bed of basalt in Tideswell Dale, Derbyshire), in coal at contact with basalt from Ayrshire (Geological Museum of Edinburgh) and from Yorkshire (Woodwardian Museum, Cambridge), in hæmatite iron-ore (*ib.*; the columns are about $\frac{1}{8}$ inch in diameter), and, though rather imperfect, in palagonite tuff (Iceland), and in a large quartz vein (Svolvær, Lofoten Islands). Ice also, when kept for some time very near a temperature of 32° Fahrenheit, as it is during a slow thaw or in those singular caverns termed glaciers, in the Alps, also exhibits a beautifully regular columnar structure, which I can only attribute to a contraction of the mass, probably as it passes from the point of minimum density to the melting-point†.

Occasionally one set of parallel divisional planes is more strongly marked than the others, so that, while the majority of the columns retain the hexagonal type, an oblong form dominates, and a somewhat platy or bedded aspect is given to the rock-mass. I remember observing this especially in a trachyte in the ravine of the cascade of the Dore, on the Pic de Sancy; and it is very conspicuous in the great mass of felsite which rises above Llyn-y-Gader (Cader Idris).

Columnar structure is rarely set up quite close to the exterior of the mass; there is usually an interval, varying from a few inches to several yards; this is either affected by some other form of jointing or is quite irregularly cracked.

Where the space intervening between the columnar part and the exterior is but small, as, for example, in "the Spindle," near St. Andrew's, Fife, and at Montiquey quarry, near Balmuto in the same county, it may be concluded that the mass soon began to lose heat very uniformly. Hence this structure is more likely to occur in intrusive masses (especially when the lava cooled at some depth like the above) than in streams of subaerial lava. In the latter also the columns often approach nearer to the under than to the upper surface. Thus the lava-stream of Royat is rudely columnar almost close to its base at the grotto of the Tirtaine, as is the stream from the eastern side of the Puy de Gravenoir, where it is exposed in a quarry on the east of the road from Clermont-Ferrand to Beaumont, while the upper part, still some yards thick, exhibits a far less

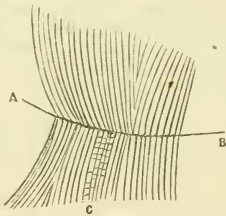
* As it may be considered to be now agreed that the sides of the prisms are normal to the surface of cooling, I shall not multiply instances to prove this.

† See 'Nature,' vol. i. p. 481, vol. iii. p. 288.

regular structure. The same may be observed in the prismatic lava at Torre del Greco (Naples), and at Fingal's Cave (Staffa).

The curved forms of the columns have been so fully discussed by Mr. Scrope and Mr. R. Mallet that I pass them by, merely stating that while some of the cases of slight flexure may be produced by a small motion of the lava-stream, after the formation of the columns, but before it has become perfectly solid, the majority must be due to changes in the form of the surface of what we may call breaking-tension in the cooling mass. It is extremely difficult to explain such complicated cases as the Clam-shell Cave (Staffa), Pouk Hill (Walsall), the Roche Sanadoire (Auvergne), and Jaujac (Ardèche); but we must remember that the surface of cooling must be closely related to the surface of the mass, and that partial denudation has often deprived us of the data for that part of the problem. Variation in the conductivity of the superincumbent materials might also produce some effect. Further complication has been sometimes introduced by large fissures, which appear to have opened out in the the mass somewhat anterior to its breaking into columns, and have allowed of a more rapid escape of heat from their surfaces. Thus columns will often be found to curve to a large, more or less horizontal joint (see fig. 1).

Fig. 1.—Columns of Trachyte curving to a joint (Pic de Sancy, near Cascade of the Dore).



A, B. Great joint. C. Minute cross-joints.

The structures more or less parallel to the surfaces of the mass, and consequently generally at right angles to the columnar, have next to be noticed. These may be roughly classified as (a) Fissile and Platy, (b) Tabular, (c) Curvitar, (d) Cup-and-ball structure.

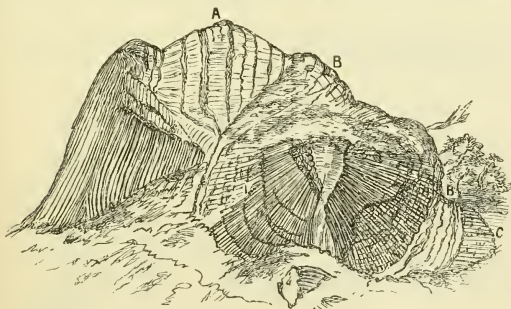
(a) *Fissile*.—A distinct tendency to a cleavage, at first sight closely resembling that of ordinary slates, is often visible in igneous rocks. A pitchstone on the north side of the hill of Dunfion (Arran) splits with tolerable ease in one direction. The great intrusive sheet of pitchstone on the Corriegills shore of the same island also has a distinctly fissile character, especially near the upper and lower surfaces, to which the structure is parallel. The same structure may be often observed near the surface of basalt dykes, as on this same shore; usually, however, it extends only for a few inches into

the mass. The outer part of the mass of basalt at the Spindle and Montiquey (mentioned above) exfoliates in rather thin plates; and the columns are, so to speak, enclosed in a fissile spheroidal shell a few inches thick.

The phenomenon is very conspicuous in some of the trachytic rocks of the Auvergne; those in the Cantal and Mont Dore are so fissile as to be used for roofing-slates. The well-known Roche Sanadoire and Roche Tuillière*, the latter of which is extensively quarried for the above purpose, are very remarkable instances of this structure, and throw much light upon its origin. I shall therefore describe them in some little detail. Near the highest part of the great Auvergne plateau, from which rise the groups of the Puy-de-Dôme volcanoes and the chain of the Pic de Sancy, and at the northern extremity of the latter, two rocky bluffs rise on either side of the deep cirque-like head of a wooded glen. That on the right bank of the valley is the Sanadoire, on the left La Tuillière. Both are phonolite; but the character of the rock†, and still more its structure, are different.

The Roche Sanadoire forms the extremity of a rather short spur from the Puy de l'Angle. On the southern side it is not very conspicuously columnar; but the rock, which is exposed in several abrupt crags, is divided into a vast number of small rather irregular prisms, with numerous cross joints. When, however, a view is gained of the precipitous western face, the columnar structure becomes more conspicuous, together with another set of divisional planes, which give a more fissile character to the rock. A reference

Fig. 2.—*Columnar and Fissile structures. Roche Sanadoire.*



A, C. Jointed columns. B. Fissile bands.

* Mr. R. Mallet (Phil. Mag. ser. 4, vol. 1. p. 218) calls the rock of La Tuillière basalt, and the fissile structure a "slaty cleavage" due to subsequent pressure. The rock is a phonolite, and has not the slightest resemblance to basalt; and the structure, I trust to show, is not a case of ordinary cleavage.

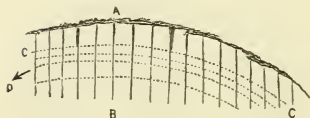
† For full account see 'Neues Jahrbuch für Mineralogie,' 1872, p. 351.

to the annexed diagram (fig. 2), together with the following extract from my note-book may make this plain :—

“The columns are frequently rather rude and quadrangular in shape; in part, however, they are tolerably regular and hexagonal. They are bent in a most singular manner, so that those toward the outside curve round and roughly overarch an interior nearly vertical sheaf or boss. These columns are cut by numerous cross joints which run parallel to great curving divisional planes, and traverse their axes at a high angle. Thus the columns appear to be built up of slabs. The cross joints are commonly not at right angles to the axis, the inclination sometimes not exceeding 50° . In parts this platy structure becomes so conspicuous as almost to obliterate the prismatic; and a very singular effect is produced by this alternation of bands of ‘frilled’ and ‘crimped’ rock. The whole mass, whether distinctly columnar or not, has more or less of a fissile structure, which is of course most distinct where the columns are least so, and is (so far as I could see, and as one would expect) parallel to the great curving divisional planes. This description applies especially to the south-western part of the hill; when a view is obtained of the whole of the western face, as from the slopes on the opposite sides of the valley, the same complicated double structure will be seen continued throughout.”

Turning now to the Roche Tuillière, we find that its eastern face is divided into a number of large columns; these are very distinctly marked, and are cut by a great number of cross joints, which are not at right angles to the axis of the columns, but dip outwards. These joints also, when viewed from a distance, are seen not to traverse the face of the cliff horizontally, but to arch upward from its two extremities so as to become horizontal in the centre,

Fig. 3.—*Diagram of Columns and Cross joints (Roche Tuillière).*



A B. Vertical joints. C C. Direction of cross joints. D. Direction of southern end of cliff.

Fig. 4.—*Fissile structure. (Roche Tuillière).*



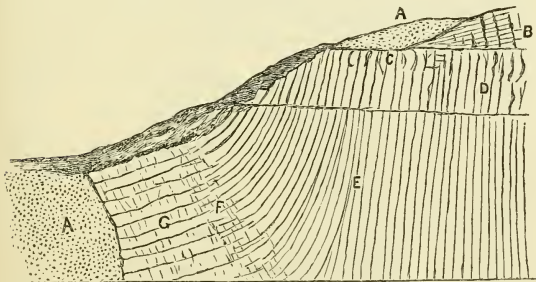
following very nearly the curve of its sky-line, which has no doubt been determined by the direction of these divisional planes. On climbing the steep wooded talus to the base of the columns their structure becomes more evident. In shape they are rather less

regular than their distant appearance would lead one to infer, as they vary from irregular quadrangular to hexagonal, the majority appearing to be pentagonal. They are often as much as 6 feet in diameter. The great cross joints cut the columns at distances from 2 to 5 feet apart; and the whole mass is traversed by a fissile structure curiously resembling that of a roughly cleaved slate, parallel to these joints. As the outward dip of these planes is some 20° , it produces a most unpleasant idea of instability upon the mind; for the columns look as if the least disturbance would cause them to slip forward. At the southern end of the cliff the columns are less distinct; and here the curve of the divisional planes makes a much higher angle with the horizon than elsewhere, becoming nearly vertical (see figs. 3 & 4).

From the above descriptions it will be evident that the fissile structure in these rocks cannot be a true cleavage; its explanation will be attempted presently.

(b) *Tabular Structure*.—In many igneous rocks the horizontal joints are so regularly and strongly defined as to produce a tabular or bedded structure. Instances of this may be seen in many granites, as, for example, at Pardenick Point, near the Land's End; in dolerite, in an intrusive mass under "the Castle," Burntisland (Fife); in the gabbro of the Gimlet rock, Pwllhelli, and of the Cuchullin Hills; and, though less perfectly, in some of the "traps" in the Lake-district. A case which I have more than once observed seems to suggest some connexion between this and the platy structure described above. An excellent example of it may be found in a quarry on the Gross Weilberg (Siebengebirge) (fig. 5). Here a mass of

Fig. 5.—Columns &c. (Gross Weilberg).



- A. Trachytic tuff. B. Closely jointed rude columns. C. Bent columns.
D. Upper stage of quarry with good columns. E. Lower stage.
F. Platy structure. G. The same in rude columns.

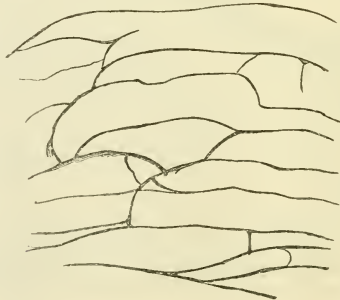
basalt is intruded into a trachytic tuff. The exterior of the mass at the top is for the space of 3 to 4 feet divided into rude quadran-

gular prisms, which are traversed by so many cross joints as to make the rock almost platy in structure; then, after a distance of about a yard, where the normal joints become rather more frequent and somewhat confused, a series of magnificent columns commences, which run with great regularity, and are singularly free from cross joints, the shafts often being unbroken for a distance of several yards. On approaching a contact with the tuff on the lower side of the mass a platy structure again sets in.

This tabular structure, it will be observed, is roughly parallel to the bounding surface of the mass, as is the bedding in the case noticed under Burntisland Castle. Intrusive dykes also sometimes show a tabular or roughly platy structure running parallel to their bounding surfaces.

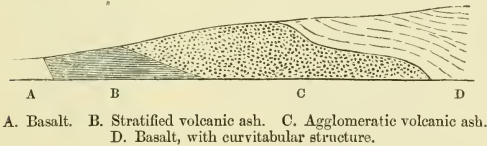
(c) *Curvitabular Structure*.—I proceed next to describe a structure which I have not often noticed myself, and do not remember to have seen described by others—which, for the sake of a name, I may denominate curvitabular jointing. As an example of it I will describe the basalt of the Plateau de Prudelle, above the valley of Villar (Auvergne), a sketch of which is engraved by Mr. Scrope, in plate vi. of his work on the Auvergne. This basalt crowns a rib or promontory of granite, resting on this or on a thin intervening bed of sandy (and ashy?) marl containing rolled felspar crystals and a few bits of scoriaceous basalt. Above the marl comes a rather irregular, hard, “ropy”-looking, brown band, probably only the baked crust of the marl, which is united irregularly to the base of the basalt flow. This is very rough, slaggy and scoriaceous, in places resembling an agglomerate of cinders, sometimes partly fused together, sometimes loose. This crust is about a foot thick, and passes rather suddenly into a somewhat slaggy-looking basalt, with a few elongated vesicles and occasional irregular vertical joints. This continues for about 2 feet; and then the curvitabular structure sets in rather suddenly. The mass is traversed by a series of more or less

Fig. 6.—*Diagram of Curvitabular structure (Plateau de la Prudelle).*



horizontal curving joints with their convexities upward; so that the whole is divided into a series of plano-convex, meniscoid, or concavo-convex blocks, in length perhaps about 2 to 4 feet, and in thickness 4 to 12 inches (fig. 6). This structure continues with but slight indications of any tendency to vertical master joints for some 35 feet; and then the basalt for the remaining space (perhaps about 4 yards) becomes rather suddenly rudely columnar*. How much has been removed by denudation from the top of the flow it is impossible to say. At the end of the spur there is evidence that its surface was uneven and a ridge already defined when the basalt flowed; for the tabular structure curves in both the longitudinal and transverse sections, so as to remain symmetrical with the surface of the ground. It is therefore evident that it is connected with the form of the surface of the rock. Close to the station of Rougeac (railway from Le Puy to Arvant) I saw a similar structure in a mass of basalt. A very rough sketch of this interesting section (jotted down from the railway-carriage window) is given below (fig. 7).

Fig. 7.—*Section at Rougeac.*



Here also the structure is affected by the form of the bounding surface; but in this case the convexities of the curves are turned downward.

(d) *Cup-and-ball Structure*.—The next structure to be noticed is that form of cross-jointing of columnar rock which goes by the name of cup-and-ball structure. Usually the columns are divided across, at variable distances, by plane cross joints at right angles to their axes. These sometimes, as in the Gross Oelberg and Weilberg (Siebengebirge), and at Murat (Département de Cantal, Auvergne), are as much as 15 or 20 feet apart; but commonly they are not more than a yard, and sometimes less. Occasionally, however, the joint-surface is not a plane, but more or less curved, so that the convex extremity of one segment fits into the concave extremity of the next. The form of this curve varies: sometimes its curvature is but slight, and it is continued down to the sides of the prism; at others the curvature is more marked, the outline of the ball being more nearly circular, and is not continued to the sides of the prism, a flat space

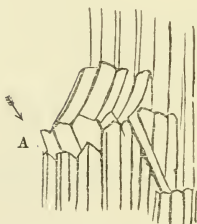
* Mr. Serope (p. 106) describes this basalt as separated at some points into very regular prisms of five or six sides, which exfoliate by decomposition in slaty laminæ at right angles to their axes. I do not remember to have seen this structure conspicuous in the part which I examined.

intervening between these and the curved boundary of the ball, which, as a rule, nowhere touches them.

These curves generally point in one direction, sometimes upward, sometimes downward; occasionally, however, cases may be noticed where they are differently directed in adjoining columns*. So far as I can remember, they are most frequent where the rock exhibits the spheroidal structure which I am about to describe; but before doing this I should wish to call attention to a curious form of cross-jointing which I observed in some of the basalt columns at the upper part of the hill of Bonnevie, Murat (fig. 8).

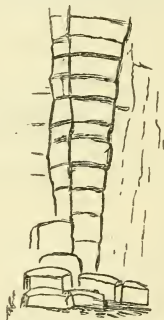
Here, in the upper part of the excavation opened for quarrying, a curious interruption to the regularity of the columns may be observed in the form of a sort of projection, like a part of a capital from which springs the base (curving till the old direction is

Fig. 8.—*Cross joints at Bonnevie.*



A. Plane of parallel joints.

Fig. 9.—*Structure of Columns in the Lava at Royat.*



resumed) of another column. A closer examination shows that this structure is connected with a series of cross joints, which cut the columns (here at angles of about 60°), and to whose plane the axes of the imperfect prisms forming the brackets are parallel. These joints are from 4'-6' apart; and the ordinary cross-jointing in the other parts of the hill seems rather regular.

A singular case of columnar and joint-structure occurs in the valley of the Tirtaine, near the grotto of the springs between Old and New Royat (Auvergne). Here the lava-stream, which is generally irregularly jointed, and sometimes (according to Mr. Scrope) spheroidal, is rudely columnar at its base (fig. 9). The columns are irregularly hexagonal, and about 18" in diameter. At first sight they seem cross-jointed at intervals of about 12" or 15";

* As is the case (pointed out by Mr. Scrope, *Geol. Mag.* Dec. 11, vol. ii. p. 412) in the columns in possession of our Society.

but on closer examination it becomes evident that this apparent division is caused by a change in the direction of the faces of the column, so that for a very short space, at this point, they are no longer vertical, but bend very slightly in or out. Nearly all these apparent bands curve a little upwards. Sometimes they correspond with actual cross joints; at others there may be very fine concealed cross joints; but in many there is not the slightest sign of any division at all. Still these bands indicate a tendency to division; for at a short distance the columns become less regular, and the real cross joints (still curving upwards) more numerous, so that the lava is first divided into irregular rectangular blocks, with curved upper and under surfaces, and then broken by irregular curving joints, which in a few cases approach the curvilinear structure already described; so that in one part the columnar, in another the curvilinear structure is dominant.

To proceed to the spheroidal structure. Professor J. Thomson regards it as the result of a process of exfoliation due to the action of the weather on a tolerably regular-shaped homogeneous mass. Though undoubtedly cuboidal blocks of rock have, for obvious reasons, a tendency to weather into rough spheroids, and though further action of the weather might occasionally produce concentric exfoliation in such spheroids, yet I trust to show that this explanation is wholly inadequate in the present case, although doubtless the weather has great effect in developing the structure. The examples which I am about to mention will, I think, establish these two propositions:—

(1) Spheroidal structure is to be seen in rocks which are not homogeneous and are not at all cuboidal in form.

(2) Spheroids may be found in columnar rock which have evidently formed inside a prism, the exterior of which was not broken by joints.

Spheroidal structure has been observed in plaster on a wall*. A very fine example of it in bedded shale is figured by Mr. Jukes in his 'Manual of Geology'†. I have seen it well developed (of an ellipsoidal form) in a lenticular fragment of shale caught up in basalt on the Fifeshire coast, near Elie. A very fine instance of it may be seen in volcanic ash near the village of Santa Lucia (Valle de Cordevole, Italian Tyrol). Here it is so conspicuous that the rock at a short distance might be readily mistaken for a decomposing basalt. Instances of it can also be found in the agglomeratic ash of the Binns, Burntisland (Fife). The annexed diagram (fig. 10) will show that here the structure is wholly independent of the form of the rock. Sometimes also it occurs where a distinct stratification may be observed, through the planes of which it cuts.

Again, perlitic‡ obsidian and pitchstone is a true case of spheroidal

* Geol. Mag. vol. viii. p. 333. † Manual of Geology, p. 311 (ed. Geikie).

‡ I distinguish, of course, perlitic from spherulitic structure. The best specimens which have come under my own notice have been from Hungary: for the opportunity of examining a very interesting example I am indebted to Mr. Judd's kindness.

roidal structure, though on a minute scale; and here examination of the rocks, both macroscopic and microscopic, proves that the structure is in no way connected with previously formed cubes, or capable of being explained by simple exfoliation during decomposition. But the following instances of its occurrence will, I think, show that no theory of mere decomposition is adequate to explain the facts.

The annexed diagram (fig. 11) is taken from a large spheroid ex-

Fig. 10.—*Spheroidal structure in Agglomerate (Burntisland).*

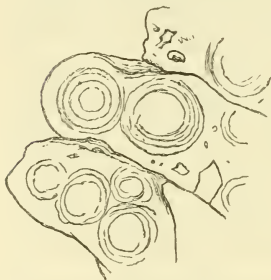
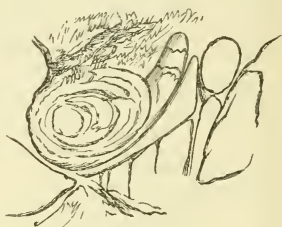


Fig. 11.—*Spheroid in Basalt near Murat.*



hibited in a mass of basalt by the roadside on the way from Murat to the bridge over the Alagnon (Auvergne). A glance at it will, I think, show that the curious prolongation of the outer layer is impossible to explain on any principle of weathering. I may add that this occurrence of an isolated spheroid or small group of spheroids in a mass which generally does not show the structure is by no means rare.

But I can produce yet stronger cases. A few kilometres from Le Puy on the Route de Brioude, close to where a road turns off to Polignac, is a mass of columnar basalt rather decomposed, part of which exhibits very well the spheroidal structure. Here spheroids may be seen, one above another, enclosed three or four at a time in a columnar shell without any dividing cross joints, so that they are just like Dutch cheeses packed in hexagonal cases (the interstices being filled up). The lid of the box has more or less fallen away, and exposed the contained spheroids (See fig. 12).

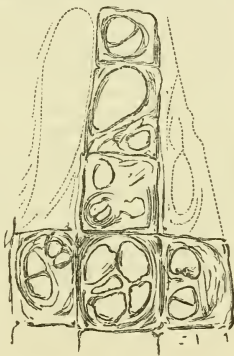
Again, a mass of trachyte, intrusive in trachytic ash, by the roadside on the flank of the Puy Gros (near the Roche Sanadoire mentioned above) showed structures bearing on this as well as other points of interest. The surface in contact with underlying tuff exhibited a platy structure for about three inches; then came a layer rudely spheroidal; above that were some irregularly vertical joints; two of these curved in opposite directions so as to enclose a

lenticular space. In this, two internal spheroids were exposed by the exfoliation of the face, which were not connected with any cross joints. In the adjoining mass four large, rude and very irregular spheroids were shown (the bounding surfaces being incomplete or with more than one centre). Similar instances of spheroids disconnected from the main joints may be seen in a quarry called Turner's Pit in the Rowley-Regis basalt, where also, in some cases, the nuclei of the spheroids are further subdivided, so that imperfect spheroids are enclosed by a spheroidal shell, like the twin kernels of a nut (fig. 13). It is therefore clear that, though the spheroids often do corre-

Fig. 12.—*Spheroids in an unjointed column near Le Puy.*



Fig. 13.—*Complicated spheroidal structure (Rowley-Regis basalt).*



spond with the spaces between cross joints in the column, there is no necessary connexion; both may be due to a somewhat similar cause; but the spheroid can exist without the cross joint, and *vice versa*.

Is it, then, possible to find any one cause which will explain these various divisional structures from the fissile to the spheroidal? I think that which has already been suggested (I may say proved) for some of them, viz. the contraction of a cooling mass, is capable of explaining all. Mr. Mallet has shown that if a mass of molten rock be cooling uniformly from a surface, it will, in consequence of the mathematical principle of least action, break into hexagonal prisms at right angles to the surface of cooling. By the same principle, if a cube were contracting in consequence of a uniform loss of heat from each of its sides, it would be more likely to rupture internally (supposing that the solidification of the exterior prevented diminution of volume) in spheroidal shells; for the more rapid loss of heat from the angles would tend to bring the isothermal surfaces within into a rudely spherical form; and then, when the strain

caused shells to be formed, they would be spherical, because the sphere is, for an equal volume, the figure of least area, and therefore of least resistance; and as its surface is at every point at right angles to the radius, there is no tangential component to the central force, and thus the whole of it is effective in rupturing. Thus a hexagon is the figure which will result from uniform contraction in two dimensions, a sphere from contraction in three dimensions.

But now, supposing that the contraction is mainly in one dimension, or, to put it otherwise, suppose that all the points lying in one surface in a body are in a state of uniform strain in one direction, naturally there would be a tendency to rupture along a surface at right angles to the strain. Suppose, for example, a number of tiles placed on a floor were subjected to strains perpendicular to the floor, they would naturally split parallel to it. Something analogous to this happens in the cooling of an igneous mass, where heat is lost from a surface (suppose the upper). The strains in a horizontal direction, due to contraction, are at once eased by the formation of joints, more or less regular; but if the loss of heat from the surface be rather rapid, there will be a strong normal strain, which will not be relieved thus, and so slabs or tabulae will be broken off by a kind of exfoliation; and the more the adjacent particles in a straight line normal to the cooling surface differ in temperature, as will be the case in rapid cooling, the more frequent will these cross joints be. Thus the mass near the surface is generally platy or tabular.

The matter may be expressed, perhaps, rather more simply in another way. Suppose a body contracting uniformly towards a point within it, and its particles incapable of differential motion; then if rupture takes place, a series of spherical shells, concentric with this point, will be formed. Suppose now (the law remaining the same) this point be in the surface of the body; then it will break in concentric hemispherical shells. Suppose the point towards which contraction takes place be outside, still the body will break into segments of large concentric spheres whose curvature will become less and less as the point becomes more remote, the limit being, of course, a plane when the distance of the point is infinite. Read, for a force causing contraction to a point, loss of heat from a surface causing contraction, and the case remains the same. When heat was lost with tolerable uniformity throughout any part of the mass, spheroids both large and small would be formed; when it was lost from a more or less plane surface, but from certain points on it more than others (which is equivalent to what would happen when cooling had advanced a little distance within a lava-stream, owing to either superficial irregularities or surface-fissures), curved cross-joints and curvilinear joints would be formed; and when cooling was taking place uniformly from all the points of a plane surface, then platy or tabular forms would result. It must also be remembered that the form of the exterior surface would greatly modify these results; for, speaking generally, all points of equal tension would lie in surfaces parallel to the exterior one, whatever it might be. Still, the principle of least action would cause a certain sym-

metry in the surface of rupture; and thus surfaces of revolution (such as spheroids, hyperboloids, &c.) would be generally produced.

There is thus a certain relation between the spheroids, the curved horizontal joints, and the great curving cross joints, such as are seen at the Roche Tuillière. Hence the fissile structure so well exhibited both here and at the Roche Sanadoire is not a *cleavage* structure in the ordinary * sense of the word; for it is the result of force acting in exactly the opposite direction, being the result of *tension*; whilst cleavage is due to compression—somewhat similar results being thus produced by forces with changed algebraic signs.

I consider the cup-and-ball joint structure a special case of the spheroidal; and the only point on which I feel some doubt is whether one should regard the division as beginning at the centre or at the exterior, or as to some extent independent,—namely, whether as a column cools tolerably uniformly, it tends by symmetry to divide into approximately equal lengths, and so spheroids are formed in the more plastic though warmer parts (the exterior shell being a little more rapidly chilled), and whether the cracks thus formed between two adjacent spheroids are continued toward the exterior, which then, being in a state of strain, is cracked horizontally at these points of weakness; or whether the exterior, cracking first, caused a line of weakness, which determined the commencement of a spheroid in the inner parts; or, as a third possibility, whether the two divisional surfaces are to some extent independent—the spheroids forming within in the more plastic part of the column, the cracks opening from without to the more solidified part, and the two surfaces of division running together at last so as to complete the separation.

Some independence in these surfaces of division seems to be indicated by the occurrence of distinctly formed spheroids in an unbroken column, and by the fact that the spheroids are occasionally again subdivided into segments which to some extent continue the same structure, two or even more of these being enclosed in a more regular spheroidal shell (see fig. 13). This independence, too, would explain the fact that the ends of columns pointing in the same direction show sometimes cups and sometimes balls. It is quite true that the divisional curves, if due to strain from contraction, should be concave to the surface of cooling, as Mr. Mallet has proved (and this, I have little doubt, is the case in the curvilinear structure); but, as Mr. Serape objects, and as my own experience has shown me, in the case of cup-and-ball structure in columns there is great uncertainty, adjacent columns showing at top, one a cup, the other a ball. If, however, the two fissures were formed to some extent independently (the curved one beginning at the interior, the plane one at the exterior), this would be likely to happen, though still the one or the other structure might predominate: the outside cracks would

* That it cannot be a true cleavage is shown (1) by the extreme improbability of this being produced in rocks which are not likely to have been subjected to great earth-movements and must have always been of rather a superficial character, and (2), in the cases quoted, by the impossibility of explaining the arrangement of the divisional planes on any theory of cleavage.

generally form at the points where the spheroid's surface was nearest to the outside of the column, because the shell would be rather weaker there.

The independence of the structures is to some extent confirmed by the fact that a thin plane lamina of rock sometimes exists between two spheroids in a column.

All the divisional structures, therefore, which can be observed in igneous rocks are, if the above considerations be admitted, to be referred to one and the same cause, viz. contraction of the mass while cooling. It is not, of course, denied that in some cases effects may have been produced by subsequent chemical or mechanical action (as the true cleavage in certain of the Welsh felstones); but it is contended that those above described are all the result of one and the same cause.

DISCUSSION.

Prof. RAMSAY inquired whether Mr. Bonney had observed the cup-and-ball structure in narrow dykes at right angles to the planes of cooling.

Mr. KOCH stated that he had tried many experiments bearing on the subject of prismatic and spheroidal structure. Slag at 1500° C., when suffered to run into water, has a perfectly smooth surface, and exhibits distinct prismatic structure. Fragments of ironstone placed on the sole of a furnace cracked off in shells, leaving spheres; and quartzite under similar circumstances flaked off in the same way.

Mr. JUDD noticed the interesting bearing of the numerous facts described in this paper on the theories concerning the production of columnar structures propounded by Prof. James Thomson and Mr. Robert Mallet. He, however, deprecated the introduction by the author of the question of the fissile structure of phonolites (which microscopic examination proved to be the result of peculiarities in the arrangement of the crystalline constituents of the rock) as having any relation to the structures resulting from contraction.

Mr. RUTLEY stated that one of the felstone dykes in the Lake-district showed spurious cleavage in the direction of the dyke.

Mr. MURPHY remarked that as the cooling commenced at the surface, the percolation of water between the first formed columns would aid in the production of the columnar structure lower down.

The AUTHOR, in reply to Mr. Judd, said that he did not regret having introduced the Auvergne phonolites into his paper, for he was convinced that their structure could not be explained by pressure; he considered that the intricacy of the arrangement shown by his diagrams negated the supposition. Separation of the minerals, as described by Mr. Judd, would not necessarily be fatal to his theory; but in the case of the Roche Sanadoire, he had examined a section to see if it existed, and had not found it.

111

